Power Quality Monitoring System under Different Environmental and Electric Conditions

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Abstract—**Power quality monitoring has become very important because it allows preventing damages on sensitive equipment. To perform a proper monitoring, it is necessary equipment with certain features: high sampling rate, portability, high-storage capacity, reconfigurability, among others. This paper presents the results of using a proprietary power quality monitoring system in three different scenarios. The system can acquire and store data for extended periods, and then data can be processed to identify power quality disturbances on the electric grid. Results show that the equipment can acquire, store and process data to identify a vast range of power quality disturbances. Moreover, environmental and electric conditions are not equal for the three locations and the equipment is able to properly work regardless these factors.**

Index Terms-- **Power quality, Current measurement, Voltage measurement, Total harmonic distortion, Voltage fluctuations.**

I. INTRODUCTION

The increase of power electronics loads, as well as the inclusion of new forms of electric generation like solar photovoltaics and wind generation, has led to serious issues in Power Quality (PQ) matter. Thus, measuring and detecting power quality disturbances (PQD) has become relevant these days because modern equipment is very sensitive to voltage and frequency variations on the power supply [1].

Due to the importance of PQ in the modern grid, some international organizations have developed standards, like the IEEE-1159 [2] and EN-50160 [3], to establish the parameters that define a specific PQD. However, information delivered by the standards is sometimes insufficient and leaves some problems unsolved. Therefore, several methodologies for the proper monitoring and identification of electric disturbances have been developed. For instance, in [4] it is presented a very complete mathematical model that describes a large set of PQD. This mathematical expression aims to be an improvement to the international standards and allows representing a large set of disturbances through a single expression. Some other works use digital signal processing techniques like short-time Fourier transform [5], wavelet transform [6], Hilbert transform [7], Kalman filter [8], and even neural networks [9] for assessing and detecting PQD. These works intend to deliver information not only of the existence of certain PQD but also of the moment of appearance of the disturbance and its duration. In this sense, these works also represent an improvement to the international standards. However, the mathematical background related to the methodologies is very complex and sometimes requires a high computational effort and much processing time.

In order to properly identify any disturbance on the electric grid, it is necessary to have a robust and reliable data acquisition system (DAS). Most of the so far reviewed articles do not provide information of the characteristics of the equipment used for the data acquisition and storage because they use synthetic signals or signal from online databases [5], [6], [8]. Some other works use their proprietary DAS [7], [9]. These devices can sample at a high rate and they use analog-to-digital converters (ADC) with a very good resolution, making them a suitable tool for data acquisition and storage tasks. Moreover, they are FPGA-based devices, which ensure that they can manage complex processing in a reduced time due to its parallel-processing characteristics. However, they are only

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tested under laboratory conditions and they have a limited memory capacity. [10] presents a smart sensor network which uses a proprietary design DAS. This system accomplishes with all the requirements listed by the international standards and can continuously monitor voltage and current signals. Additionally, it is integrated with processing capabilities for the estimation of several PQ indexes and for the identification of PQD. In addition, the system is FPGA-based, which means that it presents a high reconfigurability and flexibility being able to integrate further algorithms. The equipment described in [10] has been tested under industrial facilities and in residential home. Notwithstanding, only a few PQ indexes are presented and it is not possible to see all the functionalities of the system.

In this work, a power quality monitoring system (PQMS) is tested under different environmental and electric conditions to prove that it is robust enough to properly work at different facilities. Moreover, this work aims to show that a single system is able to provide information regarding PQ indexes and can be used to identify PQD regardless the nature of the grid. Three cases of study are included in this work: a University campus location, a solar photovoltaic plant and a wind farm. Results show that the system is a good tool for data acquisitions and storage and it is well suited for the identification of transitory events, as well as steady state disturbances so it can be used in any electric grid for PQ monitoring. Moreover, the equipment delivers good measurements even for environmental temperatures between -5 °C and 60 °C, which is suited for a wide range of applications.

II. THEORETICAL BACKGROUND

According to international standards [4-5], the term PQ refers to a wide variety of electromagnetic phenomena that cause that the waveforms of current and voltage do not fit to a purely sinusoidal waveform. There exist several disturbances related with PQ, but the most common are related with voltage signal amplitude variations (sag, swell, outage), waveform distortion (harmonics and interharmonics), sensorial perception (flicker), and transient events (impulsive and oscilatory).

A. Voltage signal amplitude variations

These PQD are referred to the root mean squared voltage *Vrms* which is defined by (1)

$$V_{rms} = \sqrt{\frac{1}{N-1}\sum_{i=0}^{N-1} v_i^2} \quad (1)$$

where N is the number of samples and v_i is the i-th sample in the voltage signal. Thus, a sag is a decrease in *Vrms* to between 0.1 per unit (pu) and 0.9 pu for durations from 0.5 cycles to 1 minute while a swell is an increase in *Vrms* above 1.1 pu for durations from 0.5 cycle to 1 minute. When the *Vrms* decreases to values lower than 0.1 pu for durations of more than 0.5 cycles it is considered as an outage.

B. Waveform distortion

The presence of harmonics and interharmonics on the voltage and current signal cause a deviation from an ideal sinusoid. A harmonic component is a sinusoidal voltage or current that is an integer multiple of the fundamental frequency of the system, and an interharmonic component is a voltage or current component having a frequency that is not an integer multiple of the fundamental frequency of the system. The magnitude of the distortion of the waveform due to harmonic contents is called total harmonic distortion (THD). To get the THD it is necessary to compute de discrete Fourier transform to obtain the signal spectrum. Then THD is defined by (2)

$$THD = \frac{\sqrt{\sum_{h\neq1}^{\infty} P_h}}{P_1} \quad (2)$$

where P_1 is the power of the fundamental frequency and P_h are the harmonics and interharmonics power.

C. Sensorial perception (Flicker)

Flicker is a low-frequency voltage fluctuation that gives rise to noticeable illumination changes in lighting equipment. Since flicker can be seen as a phenomenon that modulates in amplitude the voltage signal, it is only necessary to know the amplitude and frequency of the modulating signal to describe this phenomenon.

D. Transient events

A transient event is a sudden unexpected change on the voltage or current signal of very short duration (milliseconds). Transients can be classified into two categories, impulsive and oscillatory. An impulsive transient is a change that is unidirectional in polarity of voltage, current, or both. An oscillatory transient is a change that includes both, positive and negative polarity values, and can occur on the voltage, current or both.

III. EXPERIMENTAL SETUP

A. Power quality monitoring system

The PQMS as well as its internal components can be observed in Fig. (1). The PQMS under test in this work is designed using FPGA technology. The FPGA selected for the system is a Xilinx® Spartan6 (XC6SLX16). The PQMS can acquire data from 7 channels simultaneously: 3 channels are dedicated for voltage signals and the other four are used for measuring current signals. The device has a signal conditioning stage for the proper interpretation of the signals. This stage performs three tasks: impedance coupling, isolation for decoupling physical grounds, and filtering to avoid signal aliasing. Once the signals are well-conditioned, they go through an ADC with 8 channels from Texas Instruments® (ADS130E08). This ADC is selected because it includes a programmable gain amplifier (PGA) and an electromagnetic interference (EMI) filter, especially designed for PQ applications. The maximum operating frequency of the selected ADC is 8000 samples per second. Since the device in charge of the proper operation of the ADC is an FPGA, it is possible to configure the ADC for working at its maximum sampling rate. This is a great advantage of this system because it allows to measure frequencies up to 4 kHz, which means that it possible to identify around 80 harmonics for 50 Hz systems and nearly 66 harmonics for 60 Hz systems. Moreover, the ADC has a 16-bit resolution that guarantees an optimal representation of the acquired data and an elevated signal to noise ratio (SNR). Due to the large amount of data gathered by the system (8000 samples per second per channel), it is necessary to have a high-capacity storage system. The PQMS incorporates an external micro-SD memory to save the processed data. This is a remarkable issue, because the capacity of memory can be as large as the user needs. For very large monitoring periods, the micro-SD memory can be easily replaced once it is full, allowing to continue with the data acquisition.

a) b)

Figure 1. Power quality monitoring system a) outside, and b) inside.

The system integrates a wireless Bluetooth communication module and a universal serial bus (USB) interface. These modules allow communication between the PQMS and another device that can be a smartphone, a tablet or a personal computer (PC). This is another advantage of the system under test, because the system can be restarted, paused, stopped and monitored in a remote way. Additionally, the system includes an internal real-time clock (RTC) with 1 millisecond resolution. The RTC is used to synchronize data and it is adjusted to copy the hour of the mobile device (tablet or smartphone), when the system is restarted. It is worth noticing that this synchronization allows detecting the PQD and the hour of the day of its appearance. This could be a major advantage for identifying the source of any PQD.

Finally, the PQMS is designed to acquire voltages up to 600 Vrms. However, it can be easily modified with an external resistance to increase the range of measure. In the case of the current, the system allows to use any commercial current clamp with bayonet Neill–Concelman (BNC) connector, and output of ±1V. As well as for the voltage channels, an external resistance can be used to increment the range allowed in the current channels.

B. First case of study: Electric facility at a University campus

The PQMS is used for monitoring a building inside a University campus in Valladolid, Spain. The campus has laboratories that use electric motors and welding machines. Additionally, the building has other services like lifts, lightning, air conditioning and office equipment. The system is used for monitoring the installation 24 hours without stop. The electrical installation is composed of three phases and a neutral, each phase is at 220 Vrms and 50 Hz. The equipment acquires three voltages and four currents (including the neutral). Four commercial current clamps Fluke i3000s-FLEX are used for the current measures. This case of study can be considered as a controlled environment because temperature does not present significant variations.

C. Second case of study: photovoltaic generation

The experiment is performed at a 20 MW photovoltaic generation plant, located in central Spain. The generation is made by several branches of 100 kW each. Every branch is composed with several photovoltaic panels and a 100Kw three-phase solar inverter. In this location, two monitoring systems are used: one for the DC side of the solar inverter and another one for the AC side. Since every branch of the photovoltaic plant can deliver a DC voltage of 600 V, the DAS used in this side is conditioned to measure voltages up to 1000 V. To measure the DC current, a Hall-effect commercial current clamp HOP 500-SB/SP1 from LEM is used. On the AC side, six channels of the DAS are needed to acquire the voltage and current of the three phases. The DAS on the AC side must measure voltages up to 230 Vrms. The current clamps used on the AC side are the SCT-013-010 from YHDC. At this location, the systems are used to acquire data for a whole year. Memories with a capacity of 128 Gb are used for the data storage and they remain in the system until they reach their full capacity, equivalent to 11 days of acquisition. At this location the equipment is inside a room, near the solar inverters. The room protects the DAS from rain mainly; however, dust from the outside is always in contact with the equipment. Moreover, there are several power devices on the same room and there is no heating or air conditioning to control the temperature. Thus, the PQMS has to operate under temperatures as low as -5 °C in winter and as high as 60 °C in summer.

D. Third case of study: wind farm

This case of study takes place in a 30kW wind farm in northwest Spain. The PQMS is located at the substation of the windfarm, which means that the production of the complete farm can be monitored. The measurements are taken from a measuring transformer, so the PQMS must measure voltages up to 110 Vrms. The commercial current clamps SCT-013-010 from YHDC are used to perform the current measurements in this location. For this case of study, the system is meant to measure for an indefinite period. Thus, just like in the case of the photovoltaic central, the 128 Gb memory has to be replaced every 11 days. Once again, the PQMS is placed in a room where the temperature is not controlled, so it has to perform its work under a wide range of temperature.

IV. Results

This section presents the results of using the PQMS in the aforementioned locations.

A. First caseof study: University campus

Fig. 2 presents 10 milliseconds of the raw voltage and current signals acquired on the University campus. The sampling rate of the system as well as its resolutions allows obtaining a very detailed view of the waveforms. It is possible to see that the voltage signal is not a pure sinusoid, because the top and the bottom of the waveform are flat. This indicates that there is harmonic content on the voltage signal. The situation on the current signal is even worse. The waveform is completely distorted and does not look sinusoidal at all. International standards do not present regulations for the current signals because they are highly dependent on the loads. However, many PQD that appear on the voltage signal are related to events on the current signal. Then it is important to properly measure booth, current and voltage signal, and the PQMS is an efficient tool for this task.

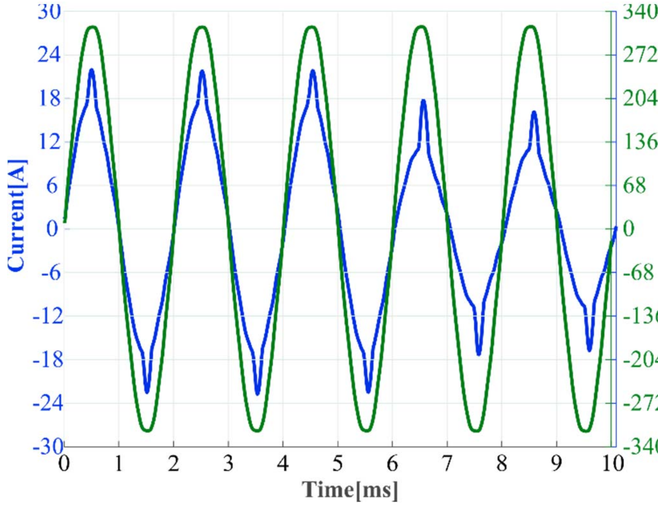

Figure 2. Raw current and voltage signals at the University campus.

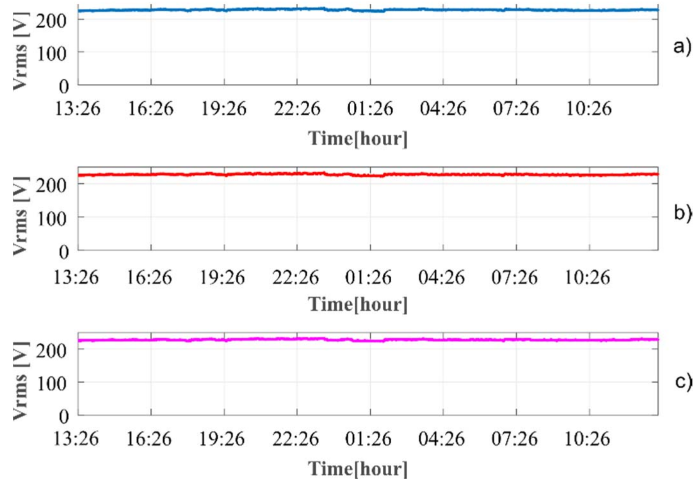

Figure 3. RMS value of the voltage signal for a) phase A, b) phase B, and c) phase C.

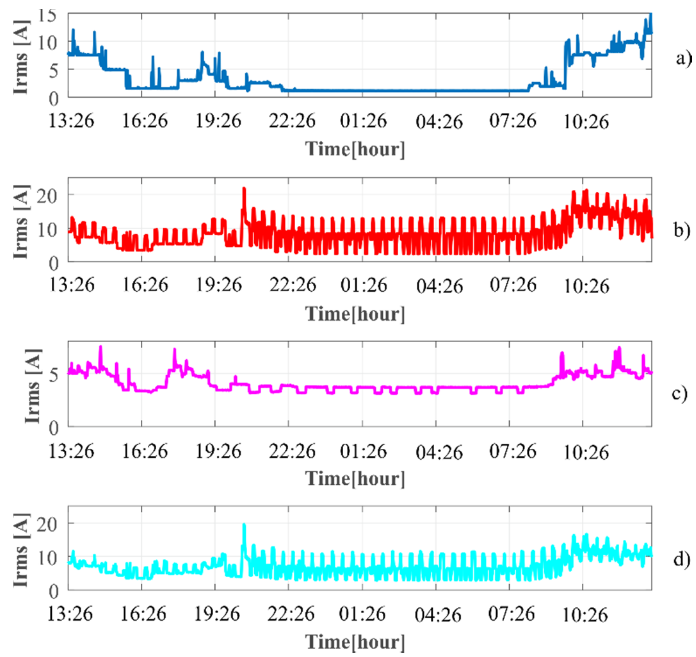

Figure 4. RMS value of the current signal for a) phase A, b) phase B, and c) phase C.

As aforementioned, the PQMS is used to monitor a 24-hour period on this location. Thus, Fig. 3 presents the RMS value of the voltage for the three phases of the electric system. It is easy to see that, although the raw signal presents some distortions (see Fig. 2), the RMS value remains very stable along the day. It is important to mention that the memory capacity of the system allows to acquire and store the complete data of the 24 hours without any loses. This is an important feature of the PQMS because most of the commercial equipment records the signal only when a PQD is detected and the record corresponds only to the duration of the disturbance. The RMS values for the current signals are also reported in Fig. 4. The profile of the signals as well as their values is very different from one phase to another. Phase A is used to feed wall plugs, and the loads for this phase are mainly office equipment. This is the reason why this phase is very active on working hours and almost inactive at night. Phase b is used for the heating and air conditioning system. The experiment in this location is performed in winter so it explains the elevated current levels and all the fluctuations on Fig. 4 b). Finally, phase c is used for illumination, lifts and vending machines. This phase presents a behavior similar to phase a, with more activity on working hours but it presents a higher consumption at night because the lights stay on. Then, from Fig. 4 it can be inferred that the electric system is unbalanced. An unbalanced system produces neutral current and the PQMS can measure it. Fig. 4 d) presents the RMS value of the neutral current of the electric system. This neutral current presents a mean value that is near to 8 A, which is a very high value considering that the neutral current should be zero.

B. Second case of study: solar PV plant.

In this scenario, the PQMS allows to identify two different PQD. The first one is an oscillatory transient that occurs in one of the current signals. Fig. 5 shows a 200-ms detail of the raw current signal. The current signal varies between ±2 A, but at a time of 95 ms occurs an oscillatory transient with a duration of around 20 ms. This event suddenly raises the current to a value of 10 A. A sudden change in current can cause severe damages on electronic equipment; therefore, it is important the measure these types of events in order to prevent them. The system can acquire the signal in a very good way and it is easy to see the behavior of the signal before, during and after the transient event. This is very useful because an analysis of the causes and consequences of a transient event could be carried out. Moreover, Fig. 6 shows that the transient event in current affects the voltage signal. It is observed that at the time that the transient in current appears, the voltage signal presents some waveform distortions. This is important because it means that the system is able to relate PQD events between current and voltage. Moreover, the RTC embedded on the PQMS allows knowing the hour of the day at what the event occurs.

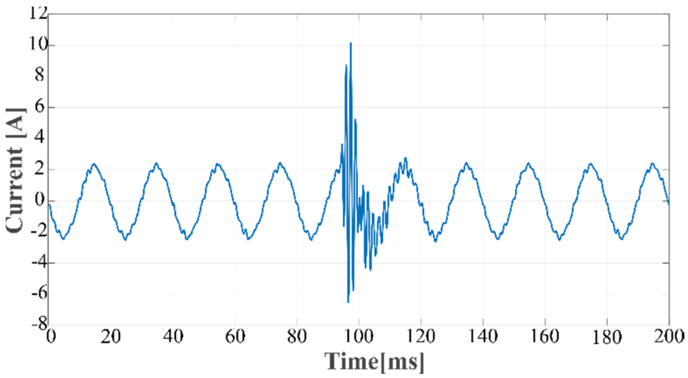

Figure 5. Oscillatory transient on one current signal from the PV plant.

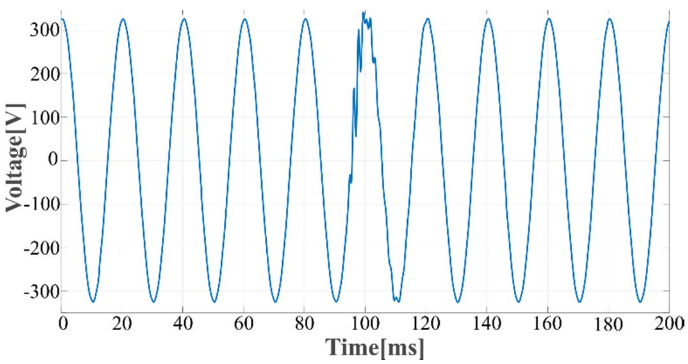

Figure 6. Oscillatory transient on one voltage signal from the PV plant.

The second PQD identified on the PV plant corresponds to flicker. Fig. 7 presents 2 minutes of a raw voltage signal. The waveform in red corresponds to the envelope of the voltage signal. It can be seen that the envelope fluctuates with time. These fluctuations of the envelope represent variations on the amplitude of the voltage signal that are not high enough to be considered as sag or swell but that can cause variations in lightning equipment or damages in sensitive electronic devices. Thus, it is possible to apply the Fourier transform to the envelope of the signal to extract the parameters that describe flicker (frequency and amplitude). Fig. 8 shows the Fourier spectra of the envelope, and it can be observed that there are three well-defined frequency components: one that is very close to 0 Hz with amplitude of around 2.5 V, another one at 24 Hz with 0.9 V of amplitude, and a third one at 26 Hz with an amplitude of 0.7 V. These frequency components describe the presence of flicker on the generation system. Since flicker is a long-duration phenomenon, it is necessary to have a device that can acquire data for extended periods, i.e., it is necessary a device with high-storage capacity. The PQMS under test accomplish with this requirement because it can acquire data for several days without interruptions.

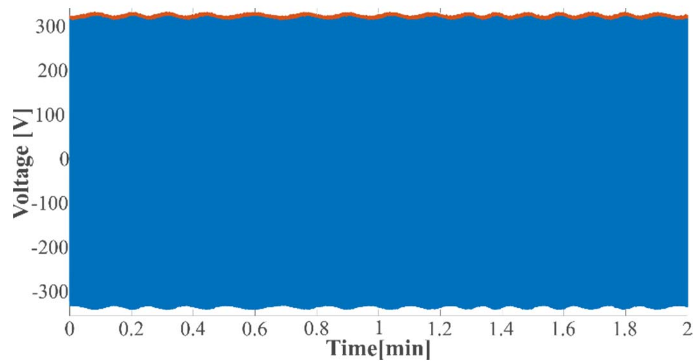

Figure 7. Raw voltage signal from the PV plant and its envelope.

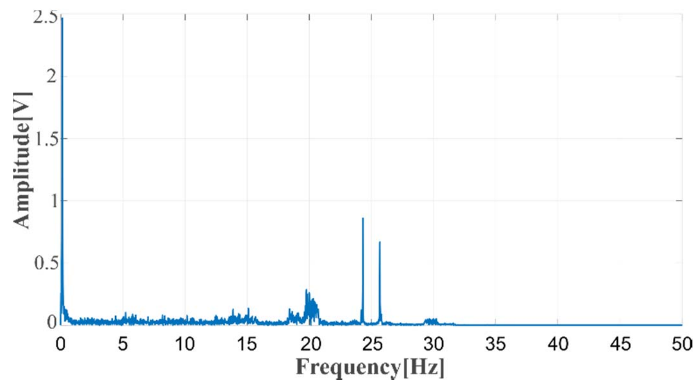

Figure 8. Fourier spectra for extraction of the parameters of flicker.

C. Third case of study: wind farm.

At this location, the system is used to detect a sag (also known as dip), on one of the voltage signals. This PQD can be observed in Fig. 9. As aforementioned, a sag is a disturbance that occurs when the amplitude of the voltage signal descends to a value lower that 0.9 p.u. Thus, to have a better appreciation of the moment when the sag appears the voltage signal is first normalized. The red dotted line in Fig. 9 represents the limit for the existence of a sag, i.e., if the voltage amplitude goes lower than the level marked by the red line it can be considered a sag. In Fig. 9 is observed that at a time of around 160 ms, the top of the voltage signal is clearly distorted and below the red dotted line. The voltage amplitude remains below this line for another two cycles and then a start rising until it stabilizes at its value of 1 again. This is a PQD of short duration (between 50 and 60 ms), and this occurs because the wind farm counts with reactive power compensation. To properly measure and assess short duration PQD, a device with a high sampling rate and good resolution is required. The PQMS proves to accomplish with these requirements.

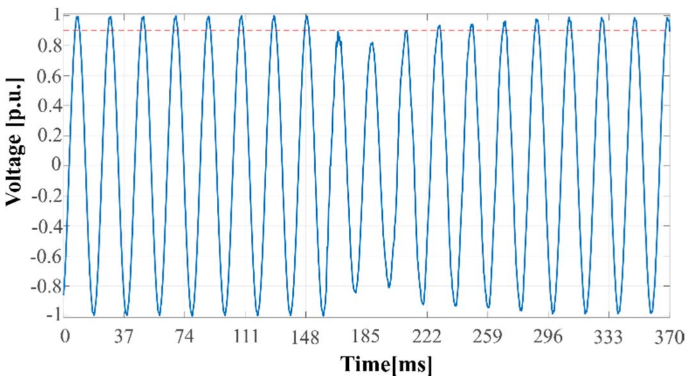

Figure 9. Sag in one voltage phase of the wind farm.

V. Conclusions

PQ monitoring is a very important task because modern electronic devices are very sensitive to fluctuations on the waveform of the electric supply. Then, it is necessary to have systems that allow continuously monitoring the electric grid to detect any disturbance. The PQMS presented in this work proved to be a portable tool for the measure and identification of several PQD. The system can be used in various locations with different ranges of measurement without suffering any changes on the design. Also, the environmental conditions, temperature, humidity, dust, etc., are not controlled for all the locations and represent no impediment for the equipment to perform its work in a very efficient way. Additionally, the system can be used to identify both: long-duration disturbances and high-duration disturbances. Moreover, the system can storage a large amount of data, so it is possible to analyze the signal not only during the appearance of a disturbance but also before and after. The PQMS presented in this work accomplishes with all the requirements set by the international standards. However, the analyses that can perform are not limited to those in the standards. Moreover, the reconfigurability of the system allows further integration of any processing task making this PQMS a robust and efficient tool for monitoring any PQD.

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